Recent Trends in Precipitation and Streamflow in the Rio Puerco Basin

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ABSTRACT

River systems in semiarid regions are susceptible to rapid and dramatic channel erosion and arroyo formation. Climate plays an important role in arroyo development through changes in precipitation intensity, seasonality, and variability. Here, trends in precipitation and streamflow at the annual, monthly, and daily timescales for the last 50 yr are analyzed for the Rio Puerco Basin in northwestern New Mexico, and connections with recent watershed and channel changes are examined. The increasing trend in annual precipitation in the basin is shown to be part of larger-scale climatic variability that affects the U.S. Southwest region, which is associated with climatic anomalies in the northern Pacific. Results of hydroclimatic data analyses point to a general increase in wetness in nonsummer months—an increase in the number of rainy days and in the frequency of flow days in the stream system is observed. There are substantial shifts in the distributions of both daily precipitation and streamflow. Rainfall with moderate intensity has been increasing, while the intensity of annual maximum rainfall events has remained largely unaffected. At the same time, the number of annual maximum runoff events in the basin has been steadily decreasing in the studied period. It is argued that recent watershed and arroyo changes that affect the rainfall–runoff relationship in the basin may be responsible for the decreasing trend in maximum runoff events. Field evidence of such changes in the Rio Puerco watershed and fluvial system is discussed.

1. Introduction

An important element of current research in climate change and variability is the analysis of trends in hydroclimatic variables from instrumental records. In the United States, numerous large-scale analyses of hydroclimatic trends have recently been conducted on precipitation and streamflow data at different timescales (e.g., Lettenmaier et al. 1994; Karl et al. 1995; Lins 1997; Karl and Knight 1998; Lins and Slack 1999). The observed hydroclimatic variability was linked to atmospheric circulation patterns such as the Southern Oscillation (e.g., Redmond and Koch 1991; Kahya and Dracup 1993; Piechota and Dracup 1996), and also to long-term sea level pressure and temperature anomalies (Mantua et al. 1997; Zhang et al. 1997; Cayan et al. 1998; Gershunov and Barnett 1998). In this paper, we add a watershed-based analysis of precipitation and streamflow trends in a semiarid environment in the U.S. Southwest region—Rio Puerco Basin, New Mexico— with emphasis placed on the connection between ob-

served changes in hydroclimatologic conditions and geomorphologic adjustment of the fluvial system.

Factors such as large spatial variability in rainfall and runoff, the flashy and intermittent nature of flow, highly erodible surface materials, and resulting extremely high sediment loads make ephemeral streams in semiarid regions susceptible to very high rates of channel erosion and filling (e.g., Leopold et al. 1966; Thornes 1977, 1994). Even slight climatic variations and trends in these regions may then have profound effects on the direction and magnitude of channel changes. The Southwest of the U.S., in particular, is a region in which deeply entrenched channels (arroyos) and active channel erosion are a common landscape feature (Bryan 1925; Schumm and Hadley 1957; Tuan 1966; Cooke and Reeves 1976; Bull 1997, and others).

There is evidence in the U.S. Southwest that channels have undergone periodic erosion and filling in the past. In the Rio Puerco Basin, the most recent period of widespread entrenchment was initiated toward the end of the nineteenth century (e.g., Bryan 1925, 1928; Cooke and Reeves 1976; Elliott et al. 1999). It has been argued that accelerated erosion was caused by 1) changes in the watershed environment induced by land use alterations (e.g., Rich 1911; Duce 1918; Bailey 1935; Bryan 1928; Thornthwaite et al. 1942; Antevs 1952, 1954) and/ or by climatic change in the region (e.g., Bryan 1940; Richardson 1945; Tuan 1966; Cooke and Reeves 1976;

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Thornes 1994); 2) temporal and spatial variability in precipitation (e.g., Dellenbaugh 1912; Gregory 1917; Bryan 1925; Leopold 1951; Balling and Wells 1990); and 3) intrinsic, threshold-dependent channel response (e.g., Schumm and Hadley 1957; Bull 1979; Graf 1979; Schumm 1973, 1980).

In this paper we explore the connection between recent geomorphologic changes in the Rio Puerco Basin and climate. We conduct a thorough examination of hydroclimatic data from the period 1948–97 in order to identify seasonality, variability, trends, and other properties of precipitation and streamflow on different timescales. On an annual timescale, trends in precipitation and streamflow over the last 50 yr are examined and connections to large-scale climate anomalies in the northern Pacific are established. Monthly data analyses identify seasonality and trends in precipitation and streamflow and, most important, they show that the principal contribution to annual trends in precipitation in the Rio Puerco come from nonsummer rainfall. Most noteworthy are analyses at the daily timescale in which we find substantive shifts in the distributions of daily precipitation and streamflow in the Rio Puerco Basin in the last 50 yr.

Analyses of hydroclimatic data are explained in the context of recent geomorphologic changes in the Rio Puerco Basin. The apparent inconsistency in trends in annual maximum precipitation and streamflow events leads us to conclude that progressive changes in vegetation and mainly hydraulic characteristics and conveyance of the channel system have occurred in the Rio Puerco Basin during the last 50 yr. This conclusion is substantiated by field observations in the arroyo stream system. Periods of channel filling and erosion in the Rio Puerco Basin will continue to alternate in the future, and we can expect that the magnitude and recurrence of these processes will reflect the state of the watershed and stream system as well as large-scale and regional climate variability and change.

2. Rio Puerco Basin and data description

The Rio Puerco is a major tributary of the Rio Grande west of Albuquerque, New Mexico (Fig. 1). It drains an area of approximately 16 000 km^2. The northeastern boundary of the watershed lies in the Sierra Nacimiento and San Pedro Mountains. In the west and southwest are the San Mateo Mountains and the Malpais, a broad plateau capped with basaltic lava. The watershed valley is covered by Tertiary and Upper Cretaceous sandstone and shale, which are very easily eroded when exposed. Modern streams in the Rio Puerco Basin are cutting into the most recent valley floodplain deposits composed predominantly of silt and sand (Bryan and McCann 1937, 1938; Wright 1946; Love 1986). Vegetation in the basin consists mostly of grassland and pinyon juniper woodland, with some sagebrush and forest. The climate of the region is semiarid (e.g., Thornthwaite et
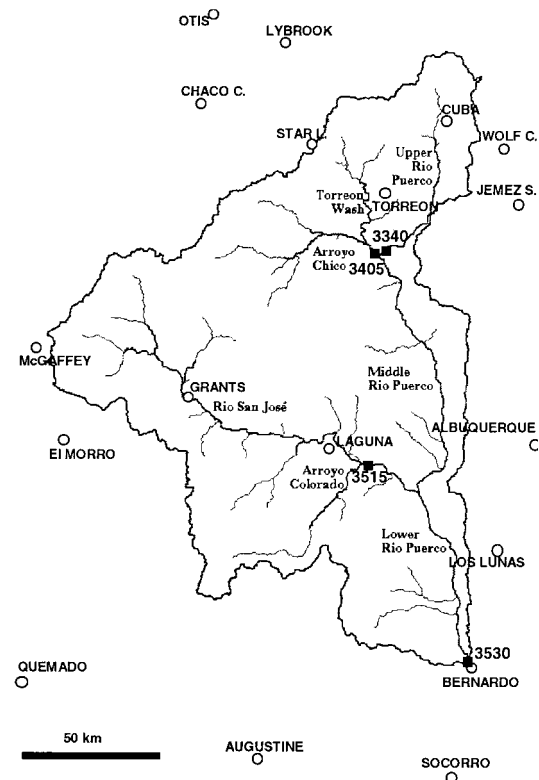

FIG. 1. The Rio Puerco Basin with locations of precipitation (circles) and streamflow (squares) gauging stations used in this analysis.

al. 1942; Antevs 1954). Elevations in the basin range from 1440 m at the outlet to 3445 m at Mount Taylor (about 2160 m at the Rio Puerco headwaters near Cuba).

The Rio Puerco main stream is approximately 270 km long. Its main tributaries are Arroyo Chico upstream and Rio San Jose downstream (Fig. 1). The river network is characterized by ephemeral and intermittent flow conditions, with high transmission losses due to infiltration. The Rio Puerco carries large amounts of suspended sediment (concentrations greater than 100 g L^{-1} are common) (e.g., Bryan 1928; Nordin 1963). Large variability in streamflow, together with great sediment-transporting capacity and availability, makes the fluvial system very susceptible to rapid channel changes.

Climate records for the Rio Puerco region used in this analysis were obtained from the National Climatic Data Center (NCDC) databases (TD3200) of the National Oceanic and Atmospheric Administration (NOAA). The National Weather Service (NWS) cooperative network of precipitation gauging stations was queried for stations lying within a quadrangle that covered the entire watershed (including a buffer zone up to 0.5° longitude and latitude). Within this quadrangle, 18 stations were identified that were in operation in 1997 and had sufficiently long records (at least 30 yr). The locations of these stations are shown in Fig. 1 and station details are listed in Table 1. Of these stations, only four were located directly inside the Rio Puerco watershed

TABLE 1. NWS cooperative network precipitation gauging station information grouped by climatic divisions (NM-01 Northwestern Plateau, NM-02 Northern Mountains, NM-04 Southwestern Mountains, NM-05 Central Valley). Thiessen weights ρ are areal weights assigned to each gauge based on the polygon method. For all gauges, records ending in 1997 were used to compute mean annual precipitation P, to find recorded maximum monthly precipitation P_{max}^{mon} and maximum daily precipitation P_{max}^{day}. For location of gauges see Fig. 1.

Station	COOP No.	Gauge datum (m)	Record since (yr)	ρ	P (mm)	P_{max}^{mon} (mm)	P_{max}^{day} (mm)
NM-01							
Chaco Canyon Nat. Mon.	291647	1881.8	1948 (50)	0.002	228	159	71
El Morro Nat. Mon.	292785	2202.8	1948 (50)	0.009	351	195	64
Lybrook	295290	2179.3	1951 (47)	0	287	166	54
McGaffey 5 SE	295560	2438.4	1949 (49)	0.0515	481	173	66
Star Lake	298524	2022.3	1953 (45)	0.0813	234	113	47
Otis	296465	2097	1957 (41)	0	257	119	51
NM-02							
Cuba*	292241	2147.3	1948 (50)	0.0535	323	135	52
Jemez Springs	294369	1909	1948 (50)	0.0066	439	179	71
Torreon Navajo Mission*	299031	2042.2	1961 (37)	0.1453	259	118	48
Wolf Canyon	299820	2505.5	1952 (46)	0.0051	586	180	85
NM-04							
Grants-Milan Air*	293682	1987.3	1953 (45)	0.2136	273	119	49
Quemado	297180	2090.9	1948 (50)	0	256	168	53
Augustine 2 E	290640	2133.6	1948 (50)	0.0015	299	180	51
NM-05							
Bernardo	290915	1443.2	1962 (36)	0.0596	212	141	57
Laguna*	294719	1773.3	1948 (50)	0.2851	238	124	73
Los Lunas 3 SSW	295150	1475.2	1957 (41)	0.0566	231	116	61
Socorro	298387	1397.5	1948 (50)	0	220	161	92
Albuquerque Int. Air.	290234	1618.5	1948 (50)	0.0293	219	85	49

* Stations are located within the Rio Puerco watershed boundary.

(Cuba, Torreon, Grants, and Laguna). The Rio Puerco Basin lies in three New Mexico NOAA climatic divisions: Northern Mountains (NM-02), Southwestern Mountains (NM-04), and Central Valley (NM-05). Daily NCDC precipitation datasets were analyzed for 14 precipitation stations that had contributing areas in the Rio Puerco watershed. The analysis of long-term climatic division averages of precipitation on a monthly and annual basis for the period 1895–1997 was also conducted on data from the NCDC Climate Database.

The Rio Puerco Basin is divided in this study into five hydrologic units: the Arroyo Chico watershed, the Rio San Jose watershed, and the Rio Puerco main stream, which consists of the Upper (upstream of the confluence with Arroyo Chico), Middle (between Arroyo Chico and Rio San Jose tributaries), and Lower (downstream of the Rio San Jose confluence) Rio Puerco watersheds (Fig. 1). Altogether there were 20 streamflow gauging stations (continuous and partial record

gauges) active in the Rio Puerco Basin at different times during the last 70 yr. Data from four stations with continuous records of daily streamflow at the outlets of main Rio Puerco subbasins and the watershed as a whole are used in this analysis: Rio Puerco above Arroyo Chico (3340), Arroyo Chico (3405), Rio San Jose at Correo (3515), and Rio Puerco near Bernardo (3530). Streamflow gauge locations are plotted in Fig. 1 and basic information is given in Table 2 (throughout this paper, gauges are generally referred to by their 4-digit identification number from Table 2). Only three of these gauges are currently in operation. Daily streamflow data were obtained from the U.S. Geological Service (USGS) National Water Information System (NWIS) Database. Monthly and annual totals were computed from daily data.

In addition to analyses for the complete periods of record shown in Table 1 and Table 2, comparisons between streamflow and precipitation were conducted on

TABLE 2. Rio Puerco USGS streamflow gauging station information. Station numbers used throughout this study are abbreviated from the NWIS standard (e.g., 08**334**000 is 3340). Gauge datum, H, and contributing drainage area, A, are taken from NWIS. Data are organized on a water year basis (starting on 1 Oct and ending on 31 Sep of the water year). Mean annual runoff, Q, is reported for the complete period of record at each gauge, and for the common period 1952–86 in brackets. For location of gauges see Fig. 1.

Station	NWIS No.	Watershed	H (m)	A (km²)	Record period (yr)	Q (10⁶ m³)
Rio Puerco above Arr. Chico	3340	Upper R. P.	1813.3	1088	1952–97 (46)	12.9 (12.2)
Arroyo Chico	3405	Arroyo Chico	1804.7	3600	1944–86 (43)	18.8 (19.1)
Rio San Jose at Correo	3515	Rio San Jose	1668.7	6553	1944–94 (51)	10.1 (10.4)
Rio Puerco near Bernardo	3530	Lower R. P.	1439.4	16110	1941–97 (57)	38.4 (37.6)

a common period of record spanning 35 yr between 1952 and 1986. Analyses with daily precipitation and streamflow data in this study are organized on a water year basis (the water year begins on 1 October and ends on 31 September of the water year).

The Rio Puerco Basin is essentially undeveloped, moderately grazed, and very sparsely populated. In the period studied here, there were no notable dams or irrigation diversions on the main stream of the Rio Puerco or any of its tributaries (with the exception of Bluewater Dam in the headwaters of the Rio San Jose Basin upstream of Grants). Although analyzed streamflow records suffer from errors induced by high suspended sediment concentrations and extreme flow variability common in ephemeral streams, they are largely free of anthropogenic effects within the watershed.

3. Method of testing for trends

Testing for trends in this study was conducted by the nonparametric Mann–Kendall test (Kendall 1938), which is commonly used for hydrologic data analysis (e.g., Hirsch and Slack 1984; Helsel and Hirsch 1992; Hirsch et al. 1993). It is a rank-based procedure especially suitable for nonnormally distributed data, censored data, data containing outliers, and nonlinear trends. The null hypothesis of randomness H_0 states that the data $(x_1, \ldots, x_n)$ are a sample of n independent and identically distributed (iid) random variables. The alternative hypothesis H_1 is that the distributions of x_k and x_j are not identical for all $k, j \leq n$ with $k \neq j$. The trend test statistic S is defined as (e.g., Hirsch et al. 1993):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k), \qquad (1)$$

where sgn( ) is the sign function.

Under H_0, the distribution of S is normal in the limit as $n \to \infty$. The mean and the variance of S, considering that there may be ties in the x series, are

$$E[S] = 0 \quad \text{and} \qquad (2a)$$

$$\mathrm{var}[S] = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right]$$
$$\div \, 18, \qquad (2b)$$

where t is the length of any given tie and Σ_t denotes the summation over all ties with length t. In this study, sequential zero values of streamflow and precipitation are considered tied censored data and are included in the sum Σ_t in Eq. (2b). The normality assumption for S is found to be good even for small n ($n \approx 10$) with a correction of ± 1, and the standard normal variate is used for hypothesis testing (e.g., Hirsch et al. 1993):

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{var}(S)}} & \text{if } S > 0 \\[2mm] 0 & \text{if } S = 0 \qquad (3) \\[2mm] \dfrac{S+1}{\sqrt{\mathrm{var}(S)}} & \text{if } S < 0. \end{cases}$$

In a two-sided test for trend, the null hypothesis is rejected at significance level α if $|Z| > Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ is the value of the standard normal distribution with a probability of exceedance of $\alpha/2$. A positive value of Z indicates an upward trend; a negative value indicates a downward trend in the tested time series. Throughout this study, trends are identified at a significance level $\alpha = 0.05$, or confidence level $\beta = 1 - \alpha = 0.95$, unless stated otherwise. The trend test statistic Z is used as a measure of trend magnitude, or of its significance. It is not a direct quantification of trend magnitude. In this study, we apply Mann–Kendall's trend test only to nonseasonal and independent data (such as annual streamflow or precipitation data, annual quantiles, and monthly data across years, etc.) and therefore we do not include adjustments that account for seasonality and serial correlation in tested data (e.g., Hirsch and Slack 1984; Helsel and Hirsch 1992).

4. Annual rainfall and runoff

Mean annual precipitation in the Rio Puerco Basin was estimated by the Thiessen polygon method. Station weights ρ are listed together with station mean annual precipitation in Table 1. Of the 18 precipitation gauging stations analyzed in Table 1, 14 stations had areas of influence inside the watershed (i.e., $\rho > 0$). The estimated mean annual precipitation in the Rio Puerco Basin from the period 1948–97 was 267 mm.

The time series of mean annual precipitation estimates over the Rio Puerco Basin constructed from station observations is shown in Fig. 2a. A linear trend line highlights the gradual increase in precipitation over the watershed in the studied period. The increase is quite dramatic: from an average of about 240 mm yr^{-1} in the 1950s to about 340 mm in the 1990s (an increase of almost 40%). Minimum precipitation was 118 mm in 1956, maximum was 430 mm in 1997, and the coefficient of variation of the precipitation record is 0.23. Trend analyses were conducted on annual precipitation data for stations with areas of influence in the Rio Puerco Basin. Results for complete records show statistically significant increasing trends at all analyzed stations except Cuba. Other researchers have also observed increases in annual precipitation for the U.S. Southwest region in the last 50 years (e.g., Lettenmaier et al. 1994; Cayan et al. 1998; Karl and Knight 1998).

Also shown in Fig. 2a is the long-term time series of annual precipitation in the Rio Puerco Basin constructed from climatic division records. The climatic division-derived series is obtained by weighting the annual av-
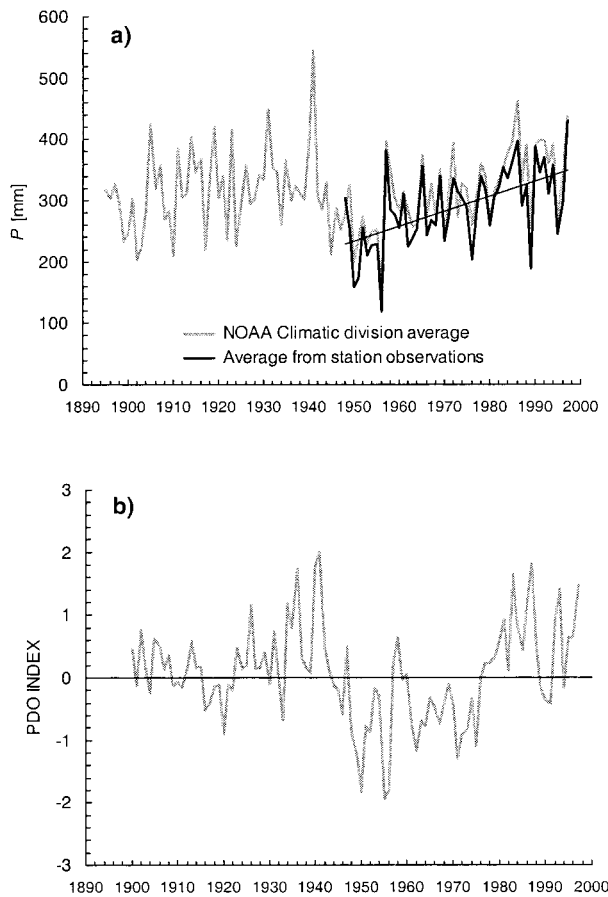
FIG. 2. (a) Time series of mean annual precipitation P over the Rio Puerco Basin from station observations (1948–97) with linear trend, and from climatic division data (1895–1997). (b) Time series of the average annual Pacific Decadal oscillation (PDO) index (after Mantua et al. 1997).

erage divisional precipitation by the area that each division covers in the basin. Divisional records differ from station-derived precipitation because they include all stations in each climatic division. It is evident from Fig. 2a that the recent increasing trend in annual precipitation is part of a larger-scale variability in precipitation. It is also noteworthy that the period of lower-than-average precipitation between 1895 and 1904 coincides with the beginning of the latest channel degradation period in northwestern New Mexico.

Several studies have attempted to relate the variability in hydroclimatic factors in the Southwest to large-scale atmospheric circulation patterns. On a shorter timescale, precipitation in the region has been found to correlate well with the El Niño–Southern Oscillation (ENSO). The general agreement is that a wet anomaly in the Southwest is observed following a warm-phase ENSO event (e.g., Redmond and Koch 1991; Piechota and Dracup 1996). Maxima in the annual precipitation record for the Rio Puerco Basin in Fig. 2a coincide with warm-phase ENSO years (e.g., 1997, 1986, 1941, 1931). On

a longer, decadal timescale, precipitation patterns in the Southwest also are significantly correlated with sea level pressure and temperature anomalies on a global scale. Wet conditions are commonly associated with low pressure anomalies in the northern Pacific, south of the Aleutian Islands (e.g., Cayan et al. 1998; Gershunov and Barnett 1998). In particular, the Pacific Decadal oscillation (PDO) index (Zhang et al. 1997; Mantua et al. 1997) correlates very well with precipitation in the Rio Puerco Basin. The annual average PDO index is shown in Fig. 2b for the period 1900–97. Positive values of PDO indicate lower sea surface temperatures and a strengthened Aleutian low pressure anomaly, which promotes a southward displacement of storm activity into the Southwest resulting in higher precipitation (e.g., Hirschboeck 1987; Webb and Betancourt 1990; Cayan et al. 1998). The correlation coefficient between average annual PDO and station-derived precipitation over the Rio Puerco Basin for the period 1948–97 is $r = 0.552$.

It is also noteworthy that the interdecadal variability in sea level pressure in the northern Pacific is characterized by regime shifts with a recurrence interval of about 50–70 yr (Minobe 1997). Although the instrumental record is not long enough to conclusively argue for 50–70 yr cycles in precipitation in the Rio Puerco Basin (see Fig. 2a), similar cycles were found by analyzing longer tree ring chronologies in the El Malpais National Monument in the southern part of the watershed (Grissino-Meyer 1995).

In contrast to precipitation, annual streamflow records in the Rio Puerco do not show the same significant increasing trend in recent decades. For the 35-yr common period from 1952–86 none of the studied gauges in Table 2 exhibited a statistically significant trend in annual streamflow. In fact, three gauges exhibited nonsignificant decreasing trends in that period (3405, 3515, 3530). The lack of statistically significant trends in annual streamflow series in the Southwest was also observed by Wahl (1992), Lettenmaier et al. (1994), Chiew and McMahon (1996), and others.

Estimates of mean annual runoff observed at Rio Puerco streamflow gauges are listed in Table 2. Highest runoff volume is generated on the average in the Arroyo Chico and Upper and Middle Rio Puerco watersheds. Rio San Jose, which drains an area almost twice the size of Arroyo Chico (see Fig. 1 and Table 2), contributes only about one-half the volume of Arroyo Chico because of upstream water use (Bluewater Lake) and the extreme permeability of the Rio San Jose Basin. Average annual outflow from the Rio Puerco Basin at Bernardo is about 38.4×10^6 m^3 yr^{-1} (1941–97). Interannual variability is fairly consistent at all gauges (the coefficient of variation for the common record ranges between 0.63 and 0.82) and interannual storage is negligible (annual correlograms show no significant autocorrelation at the 95% confidence level).

Annual streamflow in the U.S. Southwest is also correlated with ENSO events, but to a lesser degree than

precipitation (e.g., Redmond and Koch 1991; Kahya and Dracup 1993). Streamflow records integrate precipitation on a watershed scale (including the important effects of basin properties such as geology, vegetation, drainage network development, etc.). In semiarid regions, the relationship between annual precipitation and runoff is very nonlinear. In the Rio Puerco Basin, the degree of linearity in this relationship was strongest in the Upper Rio Puerco and Arroyo Chico watersheds ($r = 0.483$), which receive the highest precipitation and produce the greatest runoff per unit area (for the complete watershed $r = 0.122$). Rio Puerco annual runoff ratios are extremely low. At best, only 2%–3% of the total precipitation volume is observed as streamflow in the stream system. Average annual infiltration losses in the Middle and Lower Rio Puerco stream reaches were estimated at 4.02×10^6 m³ yr^{-1}, or about 21.8 m³ m^{-1} channel per year. This is a minimum estimate that does not account for all ungauged tributary contributions in the Middle and Lower Rio Puerco reaches (see Fig. 1). Therefore, it is not surprising that, on an annual timescale, trends in precipitation are dampened, or eliminated, by the infiltration-dominated transfer to runoff.

5. Monthly seasonality

Seasonality in precipitation and streamflow in the Rio Puerco Basin is important for geomorphologic adjustment in the arroyo stream system, because most notable channel changes are generally concentrated in the summer months with high rainfall and resulting runoff.

Precipitation seasonality is influenced mostly by the summer monsoon that brings moisture from the Gulf of Mexico and the eastern Pacific to the U.S. Southwest region (e.g., Hirschboeck 1987; Webb and Betancourt 1990; Gershunov and Barnett 1998). This is evident in Fig. 3a, which shows the seasonal distribution of mean monthly precipitation computed from gauging station data grouped by climatic division. Precipitation peaks in August, with a well-defined beginning of the summer monsoon period in July. On the average, the winter (January–March) and spring (April–June) seasons contribute 16% of precipitation to the annual total, summer (July–September) contributes 46% and autumn (October–December) 22%. Precipitation is highest in the northern portion of the Rio Puerco Basin (NM-02), while the central and southern portions (NM-05, NM-04) receive less rainfall throughout the year. Mean monthly precipitation in the peak month of August ranged from 44 mm in the Central Valley to 69 mm in the Northern Mountains division. However, maximum recorded monthly totals at individual gauges were considerably greater (see Table 1).

Trend analyses were conducted on monthly precipitation data and the mean monthly trend test statistic Z for the Rio Puerco Basin is shown in Fig. 3b. The period 1952–86 was chosen for comparison with the common period in streamflow data. Although trends in individual
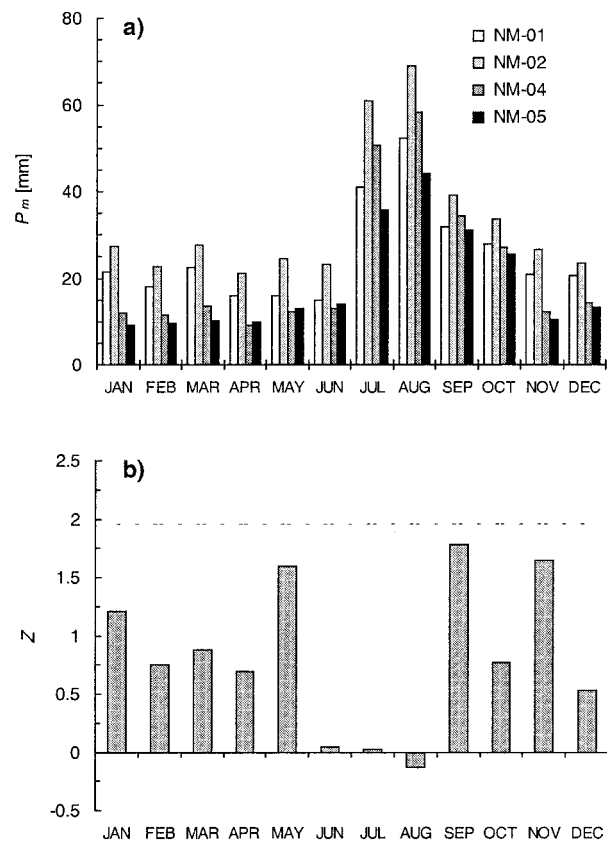

FIG. 3. (a) Seasonal distribution of mean monthly precipitation totals P_m for Rio Puerco gauges from Table 1 averaged by climatic division. (b) Rio Puerco Basin average trend test statistic Z, computed as a weighted mean of 14 gauges with contributing areas inside the watershed: $Z = \Sigma \, \rho_i Z_i / 14$; where Z_i is the test statistic for individual gauges and ρ_i is their Thiessen weight from Table 1. Statistically significant trends at the 95% confidence level have $|Z| > 1.96$. The sign of Z indicates trend direction. Analyses are for the common period of record (1952–86).

months are not statistically significant, they are consistently positive in the period from September through May and negligible in the summer months of June, July, and August. We conclude that in the Rio Puerco, the observed annual increase in precipitation is not caused by an increase in summer precipitation, but rather by an increase in precipitation totals in drier months. Other analyses of recent trends in precipitation in the Southwest region also report increases in autumn precipitation without major changes in summer precipitation (e.g., Lettenmaier et al. 1994; Karl et al. 1995). Our results suggest that the decadal variation in the Aleutian low pressure anomaly with a strong winter and spring component may be a driving force for the observed trends in Rio Puerco precipitation in those seasons (e.g., Gershunov and Barnett 1998). Seasonal correlation analyses were conducted on a monthly basis between basinwide precipitation and the PDO index. Correlation coefficients for the period February–May varied between r
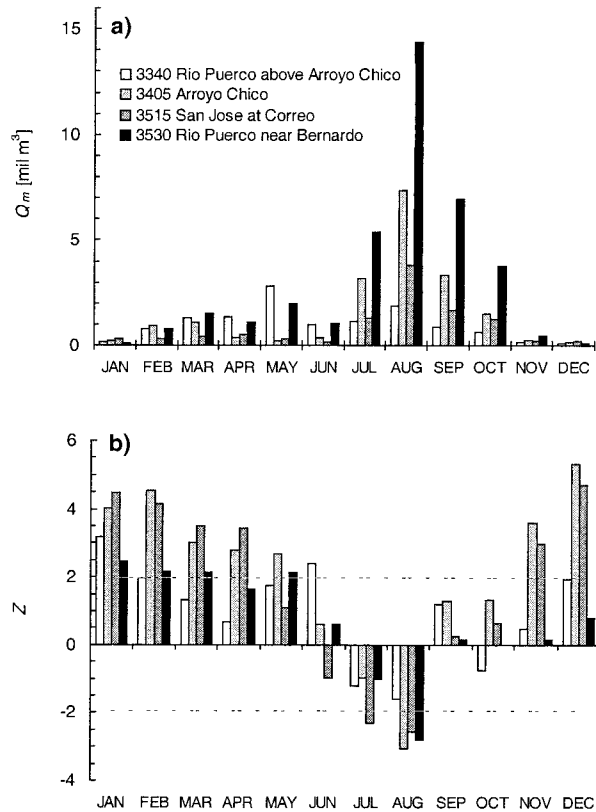
FIG. 4. (a) Seasonal distribution of mean monthly streamflow volumes Q_m at Rio Puerco gauges. (b) Trend test statistics Z for monthly streamflow totals. Statistically significant trends at the 95% confidence level have $|Z| > 1.96$. The sign of Z indicates trend direction. Analyses are for the common period of record (1952–86).

$= 0.27$ and $r = 0.39$, while correlation coefficients in remaining months were less than $r = 0.2$

The monthly distribution of mean streamflow volumes at the main gauges in the Rio Puerco Basin for the common period of record is shown in Fig. 4a. On the average, most runoff occurs between July and September (about 60%). The autumn and winter seasons each contribute only 11.5% of the total annual runoff. August is commonly the month with the highest observed runoff. In the Upper Rio Puerco watershed (3340), monthly runoff peaks in May, due to snowmelt and baseflow runoff from the mountainous regions in the northern and northeastern sections of the watershed. The average spring runoff contribution to annual runoff at gauge 3340 was 42%, while the summer season contribution was only 32%. At the same time, these contributions were 5% in the spring and 73% in the summer for Arroyo Chico (3405). At the outlet of the basin, average monthly runoff in the high-flow month of August was 14.4×10^6 m³, which is 38% of the annual total.

Results of trend analyses on monthly streamflow data for the main gauging stations are shown in Fig. 4b for the common period of record. Two important obser-

vations can be made from this figure. First, there is a consistent (and often statistically significant) increasing trend in monthly streamflow totals for the low-flow months from November through May. Second, there is a consistent decreasing trend in monthly totals in the summer high-flow months of July and August. Most noteworthy, the decreasing trend in the maximum runoff month of August is statistically significant at three of the four main stations (except 3340). Trend analyses for the complete periods of record at each gauge gave very similar results.

Seasonal trend analyses show that increasing precipitation in the autumn, winter, and spring seasons in the Rio Puerco generally translate into increasing runoff totals in those periods. In addition, despite negligible trends in summer precipitation totals, summer runoff has been steadily decreasing since 1950. This statistically significant reduction in wet-season runoff balances runoff increases in other months and results in statistically insignificant trends in annual Rio Puerco streamflow series.

6. Daily rainfall and runoff

Analyses at the daily timescale are most interesting for understanding the complex rainfall–runoff relationship in the Rio Puerco Basin, because this is the timescale of most rainfall and runoff events. Here we analyze shifts in the distributions of daily rainfall and runoff events in the studied period. Particular attention is given to recent trends in extreme annual rainfall and runoff events, because these are responsible for most notable channel changes in the stream system.

Daily rainfall and runoff in the Rio Puerco Basin are intermittent processes with mixed distributions. Their cumulative distribution functions $F(x)$ are

$$F(x) = \begin{cases} p_0 & \text{for } x = 0 \\ p_0 + (1 - p_0)G(x) & \text{for } x > 0, \end{cases} \quad (4)$$

where p_o is the probability of zero daily rainfall or runoff and $G(x)$ is the continuous cumulative distribution for nonzero values of x. The importance of the intermittency parameter p_o and the ephemeral nature of Rio Puerco streamflow are illustrated in Fig. 5, where the probability of zero flow is shown separately for every day of the year.

The behavior of p_o^d, the probability of zero flow for day d, reflects in general the seasonal distribution of streamflow found in monthly analyses. For instance, a winter–spring wet period and a summer wet period separated by a dry period (maximum p_o^d during days in June reached 0.8 at 3405 and 1.0 at 3515) are evident. During the summer period July–August p_o^d drops dramatically at all streamflow gauges. Also of interest is the prolonged dry period at the outlet of the basin (3530) in the autumn and winter months. It is clear from Fig. 5 that in this period losses due to infiltration in the Rio
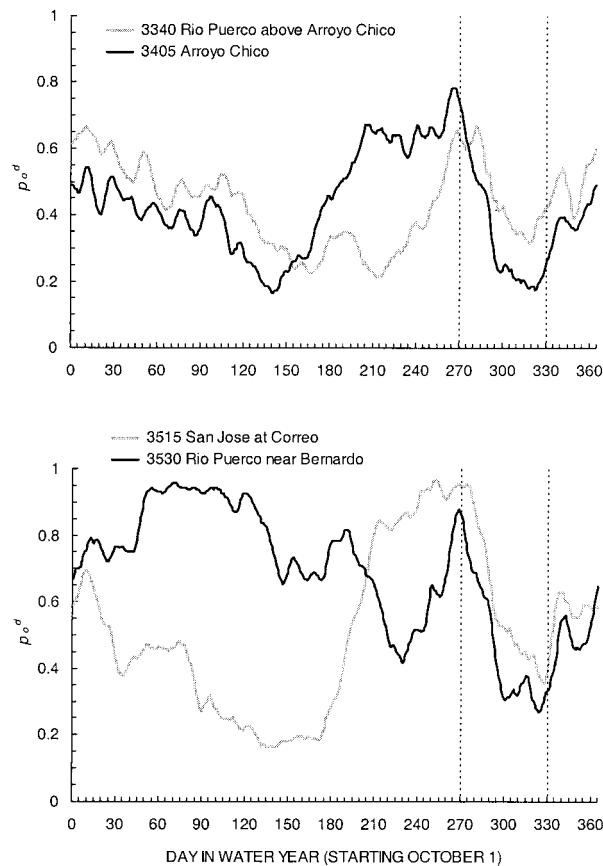
FIG. 5. The probability of zero flow p_o^d (computed for every day of the year $\alpha = 1, 365$) plotted as a 7-day moving average at stream-flow gauges in the (top) Upper Rio Puerco Basin and (bottom) Lower Rio Puerco Basin. The summer high-flow period (Jul–Aug) is out-lined. Results are for common period of record: 1952–86.

Puerco main stream are often sufficient to eliminate all channel flow before it reaches the basin outlet.

To find shifts in the rainfall and runoff distributions we constructed separate empirical cumulative distributions $F^y(x)$ (Eq. 4) for daily precipitation and streamflow on an annual basis ($y = 1, \ldots, n,$ where n is the number of analyzed years). Characteristics of these distributions, such as the annual probability of zero precipitation or streamflow p_o^y and quantiles of $F^y(x)$ and $G^y(x)$, were then analyzed for trends across years. Results are summarized in Figs. 6 and 7 and Table 3 and discussed here.

a. Trends in wetness

The annual probability of zero daily precipitation or streamflow p_o^y is used as an indicator of wetness in the basin. Mean p_o^y computed from the common record for streamflow gauges ranged between 0.43 and 0.69, and for precipitation stations between 0.69 and 0.89 (see Table 3). The trend statistic Z is also listed in Table 3. For precipitation, 11 of 14 trends in p_o^y were negative, of which 5 were statistically significant. The weighted
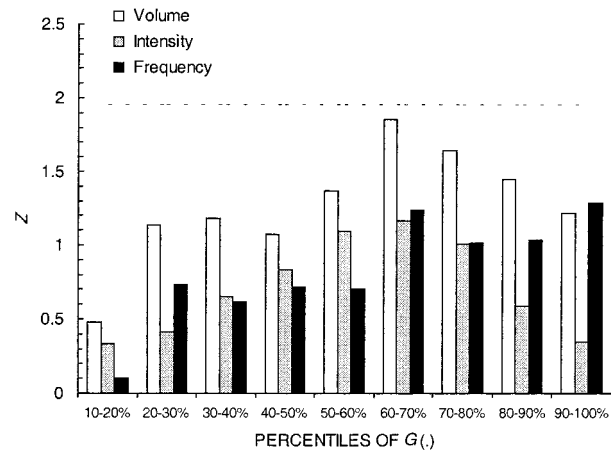

FIG. 6. The distribution of trends in daily precipitation: number of events (event frequency), average event intensity, and total volume by 10% percentile classes of the continuous distribution G (common period of record: 1952–86). The average Rio Puerco Basin trend test statistic Z was computed as in Fig. 3.
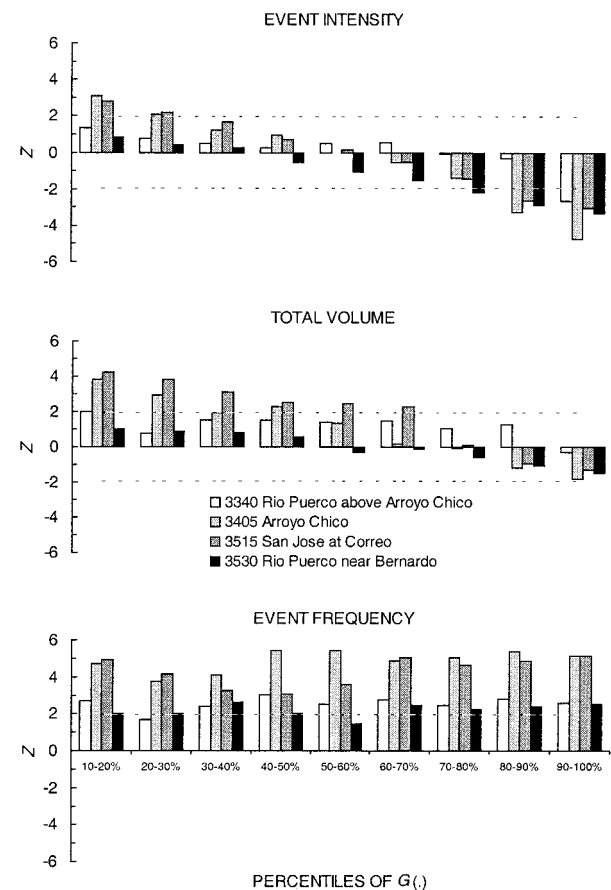

FIG. 7. The distribution of trends in daily streamflow: average event intensity, total volume, and number of events (event frequency) by 10% percentile classes of the continuous distribution G (common period of record: 1952–86) at all streamflow gauges.

TABLE 3. Rio Puerco mean annual probability of zero flow and precipitation p_o, mean daily discharge quantiles Q_p, and precipitation quantiles P_p with $p = 0.9, 0.99$ and the annual maximum for the common period of record 1952–86. In parentheses is the Z statistic of the trend test for each gauge. The sign of Z indicates trend direction. Statistically significant trends at the 95% confidence level are boldface. Average Z for Rio Puerco Basin precipitation is computed as $Z = \Sigma \rho_i Z_i / 14$; where Z_i is the test statistic for individual gauges and ρ_i is their Thiessen weight from Table 1.

Streamflow	p_o	$Q_{0.9}$ (m³ s⁻¹)	$Q_{0.99}$ (m³ s⁻¹)	Q_{max} (m³ s⁻¹)
3340	0.43 (−**2.56**)	1.08 (1.28)	5.5 (−1.82)	13.6 (−**2.68**)
3405	0.43 (−**5.41**)	0.77 (1.61)	14.3 (−**3.61**)	36.5 (−**3.28**)
3515	0.52 (−**5.07**)	0.41 (1.19)	7.41 (−**2.07**)	21 (−**3.08**)
3530	0.69 (−**2.36**)	2.01 (0.44)	28.8 (−**2.44**)	54.2 (−**2.83**)

Precipitation	p_o	$P_{0.9}$ (mm)	$P_{0.99}$ (mm)	P_{max} (mm)
Chaco C.	0.84 (−1.38)	1.3 (0.85)	13 (1.14)	25.3 (0.19)
El Morro	0.78 (−1.61)	2.8 (**2.71**)	16.3 (**3.1**)	29.3 (0.51)
McGaffey	0.82 (−0.91)	4.1 (**2.19**)	20.5 (1.45)	35.5 (0.44)
Star Lake[a]	0.83 (−**2.6**)	1.5 (1.92)	12.2 (0.02)	22.6 (0.45)
Cuba	0.82 (0.1)	2.4 (0.87)	18 (0.82)	29.6 (−0.6)
Jemez Spr.	0.78 (−1.53)	3.2 (1.79)	20.4 (−0.26)	33.5 (0)
Torreon[b]	0.84 (0.02)	1.6 (0.75)	14.3 (**3.25**)	29.1 (0.77)
Wolf C.[c]	0.69 (−1.11)	5 (1.87)	22.9 (1.16)	34.8 (−0.22)
Grants[d]	0.84 (**2.58**)	1.7 (**2.11**)	14.8 (1.28)	29.2 (−0.57)
Augustine	0.83 (**2.67**)	1.5 (**2.76**)	15.8 (**2.73**)	28.8 (**3.48**)
Bernardo[e]	0.89 (−0.32)	0.4 (0.92)	15 (1.56)	28.2 (1.19)
Laguna	0.86 (−**3.78**)	1.1 (**3.58**)	14.7 (0.82)	29.3 (0.28)
Los Lunas[f]	0.88 (−**4.05**)	0.7 (**3.05**)	14.7 (0.62)	28.3 (−1.56)
Albuquerque	0.84 (−**2.76**)	1.1 (**2.83**)	12.7 (1.59)	25.1 (0.77)
RIO PUERCO	0.85 (−1.14)	1.6 (**2.26**)	15 (1.31)	28.8 (0.11)

[a] Record period is water year 1954–86 ($n = 33$ yr).
[b] Record period is water year 1962–86 ($n = 25$ yr).
[c] Record period is water year 1953–86 ($n = 34$ yr).
[d] Record period is water year 1954–86 ($n = 33$ yr).
[e] Record period is water year 1963–86 ($n = 24$ yr).
[f] Record period is water year 1958–86 ($n = 29$ yr).

Rio Puerco average was $Z = -1.14$. For streamflow, decreasing trends were statistically significant at all gauges. For instance, at the Upper Rio Puerco and Arroyo Chico gauges, p_o^y decreased from about 0.7 in the early 1950s to about 0.1 after 1983 (in 1983, 1984, and 1986 there were absolutely no dry days recorded at the Arroyo Chico gauge). The streamflow records show that there is a significant basinwide increasing trend in the number of days with observed flow in the Rio Puerco in the studied period.

b. Trends in event frequency, intensity, and volume

Trend analyses were also conducted on the number of events, average event intensity and total rainfall and runoff volume in 10% percentile classes extracted from the continuous cumulative distribution function $G^y(x)$.

The results for precipitation in the form of a basin-averaged trend test statistic are shown in Fig. 6. Although none of the trends are statistically significant, there is a general increase in both precipitation intensity and frequency throughout the distribution, leading to an increasing trend in precipitation volume. The increase in average precipitation intensity is highest in the 50%–80% range. However, in terms of volume, the contribution of the highest percentile range to the annual total is greatest.

The results for streamflow are shown in Fig. 7. It is clear from this figure that runoff event frequency has been increasing steadily (and significantly) throughout the distribution. However, the daily streamflow rate (event intensity) has generally been decreasing for the upper 30% of the events every year, and increasing in the lower percentile classes. As a result, streamflow volume in the studied period has generally been decreasing in the highest 10% percentile class. Figure 7 illustrates well that despite only marginal trends in annual streamflow volumes, there have been substantive changes in the distributions of daily streamflows at all Rio Puerco streamflow gauges in the recent record. While the Rio Puerco stream system does seem to be getting wetter (in terms of observed runoff) in the studied period, this increase in runoff is coming from low to moderate runoff events, and the intensity of extreme annual events is actually decreasing in this period. Trend analyses using complete records at all precipitation and streamflow gauges gave the same general results.

c. Trends in extreme annual events

Annual streamflow and precipitation quantiles x_p^y were obtained from empirical annual cumulative dis-

tribution functions $F^y(x)$ for chosen nonexceedance probabilities p:

$$p = P(X \leq x_p^y) = F(x_p^y). \tag{5}$$

The annual quantile x_p^y is a daily streamflow or precipitation magnitude that in a given year y was exceeded $100(1 - p)\%$ of the time. The time series of annual quantiles x_p^y allows us to study the trends in daily flow or precipitation magnitudes with the same probability of exceedance every year. As an example, average streamflow and precipitation quantiles with $p = 0.9$, 0.99, and the annual maximum are listed together with the results of trend analyses in Table 3. For precipitation, we found that the average intensity of the maximum daily rainfall event in each year has not been (significantly) changing during the common record (only one station showed a statistically significant increasing trend in P_{max}). At the same time, there has been a general increase in quantiles in the range $0.9 < p < p_{max}$. For streamflow, the shift in the distribution was quite different. Quantiles with $p < 0.95$ generally exhibited an increasing trend, while quantiles with $p > 0.95$, including the annual maximum, exhibited a decreasing trend. The upward trend in streamflow in the period 1952–86 is statistically significant at all stations (except 3530) for p ranging from 0.4 to 0.8 (not shown in Table 3). The downward trend is statistically significant for the annual maximum observed flow at all gauges. Complete records gave only marginally different results.

The discrepancy between trends in annual maximum rainfall events (Karl et al. 1995; Karl and Knight 1998) and runoff events (Lins and Slack 1999) has been observed in other parts of the United States, and it has important implications for the role of climate change in geomorphologic adjustment. Some reasons for this discrepancy in the Rio Puerco Basin are addressed in the following discussion.

7. Discussion

Analyses of recent trends in precipitation and streamflow in the Rio Puerco in this paper reveal several interesting features of this semiarid basin. At the annual timescale, a statistically significant increasing trend in precipitation in the basin was detected in the 1948–97 period. This trend was not evident in streamflow data. Analyses of seasonal precipitation showed that the consistent increase in annual precipitation does not come from the summer monsoon period, but rather from an increase in precipitation in the autumn and spring months promoted by a strengthened low pressure anomaly in the northern Pacific. Monthly streamflow totals also showed consistently increasing trends in the low-flow months but a consistently decreasing trend in the high-flow months of July and August. Most notable are results at the daily timescale, which illustrate that the Rio Puerco Basin is getting wetter in terms of the number of rainy days and mostly in terms of the frequency

of observed runoff in the stream system. For precipitation, increasing trends in event intensity are concentrated in the moderate rainfall intensity range, but precipitation quantiles of the highest intensity (annual maxima) remain fairly constant (with an average basinwide intensity of about 29 mm day^{-1}). For streamflow, increasing trends in event frequency are apparent across the whole range of the distribution. However, the intensity of annual maximum events is systematically and significantly decreasing at all Rio Puerco gauges (at the outlet the average annual maximum flow was 54.2 m^3 s^{-1}).

One of the goals of our study was to interpret the observed hydroclimatic trends in the context of recent geomorphologic changes in the Rio Puerco Basin. In this sense it is particularly appropriate to concentrate on annual extreme rainfall and runoff events because they have been shown to initiate significant trenching in ephemeral channels in semiarid environments (e.g., Leopold 1951; Schumm and Hadley 1957; Tuan 1966; Schumm 1973; Balling and Wells 1990). It is evident from the analysis in this paper that annual maximum precipitation events seem to be producing progressively lower annual maximum runoff events in the Rio Puerco in the last 50 yr. The two most probable reasons for this are 1) vegetation changes in the basin that delay overland flow and increase infiltration and 2) changes in the hydraulic characteristics of the stream system that decrease the conveyance of the channels and increase transmission losses. In the following discussion we explore evidence for these statements in the Rio Puerco Basin.

Vegetation changes in the Rio Puerco Basin in the last 50 yr are difficult to document because of large seasonal and interannual variability in vegetative cover and limited data. However, based on experiments and observations in a subbasin of the Arroyo Chico, Branson and Janicki (1986) argue that in the period 1958–79 a dramatic increase in live vegetation cover took place in the Rio Puerco. They attribute this improvement mainly to increases in precipitation in this period, with a decrease in grazing intensity as a secondary cause. An increase in vegetative cover would positively affect infiltration, reduce hillslope erosion and runoff. Regarding the effects of grazing it is important to note that although irrigated agriculture was practiced in the Rio Puerco Basin together with cattle and sheep grazing in the nineteenth century, almost all permanent settlements in the Upper and Middle Rio Puerco Basins were abandoned after 1880. As a result, livestock grazing in the basin has also decreased dramatically since the 1930s to a relatively stable level in recent years.

Changes in the conveyance of the Rio Puerco arroyo stream system seem to be a stronger contributor to recent trends in intense runoff events. In his detailed study, Elliott (1979) observed a distinction between upstream and downstream reaches in the Rio Puerco arroyo system. Upstream reaches generally had a large channel

width:depth ratio (mean 78.3), contained less silt and clay (mean 23.7%) and had unstable banks, less vegetation, and a laterally shifting channel. Downstream reaches had a smaller width:depth ratio (mean 12.2), larger amount of silt and clay (mean 44.9%), more resistant and steeper banks, dense riparian vegetation, and a more stable channel position within the floodplain. In 1935 photos, most of the stream system appeared to be similar to the upstream reach type. Between 1935 and 1979 the Lower and Middle Rio Puerco reaches have seen aggradation and stabilization of their inner floodplain and the establishment of permanent riparian vegetation. Recent surveying shows this development to be progressing upstream (J. Elliott 1999, personal communication). A decrease in sediment concentration at the outlet of the basin between 1948 and 1996 (Elliott et al. 1999) has also accompanied the general alluviation of the Rio Puerco stream system in that period. It can be expected that flood conveyance has decreased in those sections of the Rio Puerco where the channel is narrower and the floodplain is well vegetated. The gradual recovery of riparian vegetation is also likely responsible for increasing water loss due to evapotranspiration and floodplain infiltration of overbank flow.

Results suggest that periods of alluviation in the Rio Puerco arroyo system may be connected with persisting wetter conditions in the basin that are favorable to vegetation recovery in conjunction with fewer high-intensity rainstorms. The importance of changes in precipitation intensity for arroyo development and evolution has been emphasized in the past (Leopold 1951; Cooke and Reeves 1976; Balling and Wells 1990, and others).

Geomorphologic changes in the Rio Puerco arroyo system are continuous, with phases of alluviation followed by phases of degradation. Periodically this process seems to intensify and produce rapid entrenchment episodes that lead to arroyo formation and development. Certainly many factors can contribute to this intensification, but it is likely that climate plays a leading role. An interesting development in the possible prediction of the erosion cycles in the Rio Puerco Basin lies in their connection with persistent large-scale climate anomalies, such as the PDO discussed in this paper (e.g., Latif and Barnett 1994; Cayan et al. 1998). This remains an interesting research topic.

Analyses in this paper indicate that climate change and arroyo development in the Rio Puerco Basin are closely linked, and that climatic variability in semiarid environments at different timescales can provide a wealth of information that can be used to assess the state and behavior of their channel systems. The study of the Rio Puerco Basin is still in progress. The authors are currently developing a hydraulic–sediment transport model to quantify long-term channel erosion processes in the watershed. More information about ongoing Rio Puerco research can be found at http://climchange. cr.usgs.gov/rio_puerco.

REFERENCES

Antevs, E., 1952: Arroyo cutting and filling. *J. Geology,* **60,** 375–385.

——, 1954: Climate of New Mexico during the last glacio-pluvial. *J. Geology,* **62,** 182–191.

Bailey, R. W., 1935: Epicycles of erosion in the valleys of the Colorado Plateau province. *J. Geology,* **43,** 337–355.

Balling, R. C., and S. G. Wells, 1990: Historical rainfall patterns and arroyo activity within the Zuni River drainage basin, New Mexico. *Ann. Assoc. Amer. Geog.,* **80,** 603–617.

Branson, F. A., and A. Janicki, 1986: Botanic and hydrologic changes on rangelands of the Rio Puerco Basin, New Mexico. U.S. Geol. Surv. Water-Resources Rep. 86-4021, 23 pp.

Bryan, K., 1925: Date of channel trenching (arroyo cutting) in the arid Southwest. *Science,* **62,** 338–344.

——, 1928: Historic evidence on changes in the channel of Rio Puerco, a tributary of the Rio Grande in New Mexico. *J. Geology,* **36,** 265–282.

——, 1940: Erosion in the valleys of the Southwest. *N. Mexico Quart.,* **10,** 227–232.

——, and F. T. McCann, 1937: The Ceja del Rio Puerco: A border feature of the basin and range province in New Mexico, I. Stratigraphy and structure. *J. Geology,* **45,** 801–828.

——, and ——, 1938: The Ceja del Rio Puerco: A border feature of the basin and range province in New Mexico, II. Geomorphology. *J. Geology,* **46,** 1–16.

Bull, W. B., 1979: Threshold of critical power in streams. *Geol. Soc. Amer. Bull.,* **90,** 453–464.

——, 1997: Discontinuous ephemeral streams. *Geomorphology,* **19,** 227–276.

Cayan, D. R., M. D. Dettinger, H. F. Diaz, and N. E. Graham, 1998: Decadal variability of precipitation over western North America. *J. Climate,* **11,** 3148–3166.

Chiew, F. H. S., and T. A. McMahon, 1996: Trends in historical streamflow records. *Regional Hydrological Response to Climate Change,* J. A. A. Jones et al., Ed., Kluwer Academic, 63–68.

Cooke, R. U., and R. W. Reeves, 1976: *Arroyos and Environmental Change in the American South-West.* Clarendon Press, 213 pp.

Dellenbaugh, F. S., 1912: Cross-cutting and retrograding of streambeds. *Science,* **35,** 656–658.

Duce, J. T., 1918: The effect of cattle on the erosion of canyon bottoms. *Science,* **47,** 450–452.

Elliott, J. G., 1979: Evolution of large arroyos: The Rio Puerco of New Mexico. M.S. thesis, Earth Resources Dept., Colorado State University, 106 pp.

——, A. C. Gellis, and S. B. Aby, 1999: Evolution of arroyos: Incised channels of the southwestern United States. *Incised River Channels,* S. E. Darby and A. Simon, Eds., John Wiley and Sons, 153–185.

Gershunov, A., and T. P. Barnett, 1998: Interdecadal modulation of ENSO teleconnections. *Bull. Amer. Meteor. Soc.,* **79,** 2715–2725.

Graf, W. L., 1979: The development of montane arroyos and gullies. *Earth Surf. Processes,* **4,** 1–14.

Gregory, H. E., 1917: Geology of the Navajo country. *U.S. Geol. Surv. Prof. Pap.* **93,** 161 pp.

Grissino-Meyer, H. D., 1995: Tree-ring reconstructions of climate

and fire history at El Malpais National Monument, New Mexico. Ph.D. dissertation, University of Arizona, 250 pp.

Helsel, D. R., and R. M. Hirsch, 1992: *Statistical Methods in Water Resources. Studies in Environmental Science.* Elsevier, 522 pp.

Hirsch, R. M., and J. R. Slack, 1984: A nonparametric trend test for seasonal data with serial dependence. *Water Resour. Res.,* **20,** 727–732.

——, D. R. Helsel, T. A. Cohn, and E. J. Gilroy, 1993: Statistical analysis of hydrologic data. *Handbook of Hydrology,* D. R. Maidment, Ed., McGraw-Hill, Inc., 17.1–17.55.

Hirschboeck, K. K., 1987: Catastrophic flooding and atmospheric circulation anomalies. *Catastrophic Flooding,* L. Mayer and D. Nash, Eds., Allen and Unwin, 23–56.

Kahya, E., and J. A. Dracup, 1993: U.S. streamflow patterns in relation to the El Niño–Southern Oscillation. *Water Resour. Res.,* **29,** 2491–2503.

Karl, T. R., and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Meteor. Soc.,* **79,** 231–241.

——, ——, and N. Plummer, 1995: Trends in high-frequency climate variability in the twentieth century. *Nature,* **377,** 217–220.

Kendall, M. G., 1938: A new measure of rank correlation. *Biometrika,* **30,** 81–93.

Latif, M., and T. P. Barnett, 1994: Causes of decadal climate variability over the North Pacific and North America. *Science,* **266,** 634–637.

Leopold, L. B., 1951: Rainfall intensity: An aspect of climatic variation. *AGU Transactions,* **32,** 347–357.

——, W. W. Emmett, and R. M. Myrick, 1966: Channel and hillslope processes in a semiarid area, New Mexico. U.S. Geol. Surv. Prof. Pap. 352-G, 253 pp.

Lettenmaier, D. P., E. F. Wood, and J. R. Wallis, 1994: Hydro-climatological trends in the continental United States, 1948–88. *J. Climate,* **7,** 586–607.

Lins, H. F., 1997: Regional streamflow regimes and hydroclimatology of the United States. *Water Resour. Res.,* **33,** 1655–1667.

——, and J. R. Slack, 1999: Streamflow trends in the United States. *Geophys. Res. Lett.,* **26,** 227–230.

Love, D. W., 1986: A geological perspective of sediment storage and delivery along the Rio Puerco, central New Mexico. *Drainage Basin Sediment Delivery,* R. F. Hadley, Ed., IAHS Publication 159, 305–322.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.,* **78,** 1069–1079.

Minobe, S., 1997: A 50–70 year oscillation over the North Pacific and North America. *Geophys. Res. Lett.,* **24,** 683–686.

Nordin, C. F., 1963: A preliminary study of sediment transport parameters, Rio Puerco near Bernardo, New Mexico. U.S. Geol. Surv. Prof. Pap. 462-C, 21 pp.

Piechota, T. C., and J. A. Dracup, 1996: Drought and regional hydrologic variation in the United States: Associations with the El Nino–Southern Oscillation. *Water Resour. Res.,* **32,** 1359–1373.

Redmond, K. T., and R. W. Koch, 1991: Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resour. Res.,* **27,** 2381–2399.

Rich, J. L., 1911: Recent stream trenching in the semi-arid portion of Southwestern New Mexico, a result of removal of vegetation cover. *Amer. J. Science,* **32,** 237–245.

Richardson, H. L., 1945: The significance of terraces due to climatic oscillation. *Geol. Magazine,* **82,** 16–18.

Schumm, S. A., 1973: Geomorphic thresholds and complex response of drainage systems. *Fluvial Geomorphology,* M. Morisawa, Ed., Allen and Unwin, 299–310.

——, 1980: Some applications of the concept of geomorphic thresholds. *Thresholds in Geomorphology,* D. R. Coates and J. D. Vitek, Eds., Dowden and Culver, 473–485.

——, and R. F. Hadley, 1957: Arroyos and the semiarid cycle of erosion. *Amer. J. Science,* **255,** 161–174.

Thornes, J. B., 1977: Channel changes in ephemeral streams: Observations, problems, and models. *River Channel Changes,* K. J. Gregory, Ed., John Wiley and Sons, 317–335.

——, 1994: Channel processes, evolution, and history. *Geomorphology of Desert Environments,* A. D. Abrahams and A. J. Parsons, Eds., Chapman and Hall, 288–317.

Thornthwaite, C. W., C. F. Sharpe, and E. F. Doesch, 1942: Climate and accelerated erosion in the arid and semiarid Southwest, with special reference to the Polacca Wash drainage basin, Arizona. Department of Agriculture Tech. Bull. 808, 134 pp.

Tuan, Y., 1966: New Mexican gullies: A critical review and some recent observations. *Assoc. Amer. Geog. Ann.,* **56,** 573–597.

Wahl, K. L., 1992: Evaluation of trends in runoff in the western United States. *Proc., Managing Water Resources During Global Change, 28th Annual Conf. and Symp.,* Reno, NV, Amer. Water Resour. Assoc., 701–710.

Webb, R. H., and J. L. Betancourt, 1990: Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. U.S. Geol. Surv. Open-File Rep. 90-553, 69 pp.

Wright Jr., H. E., 1946: Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico. *Geol. Soc. Amer. Bull.,* **57,** 383–456.

Zhang, Y., J. M. Wallace, and D. S. Battisti, 1997: ENSO-like interdecadal variability: 1900–93. *J. Climate,* **10,** 1004–1020.